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Calculated temperature field in and around repository for spent nuclear fuel

T Tarandi

VBB, Sweden, april 1983

SVENSK KÄRNBRÄNSLEFÖRSÖRJNING AB / AVDELNING KBS

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ERRATA

KBS Technical Report 83-22

Calculated temperature field in and around a repository for spent nuclear fuel.

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Please correct on page 21 the text for
FIG 11 D

reads: VARIATION OF TEMPERATURE AT CENTRUM
ALTERNATIVE 14 A

should read: VARIATION OF TEMPERATURE AT CENTRUM
ALTERNATIVE 14 C

CALCULATED TEMPERATURE FIELD IN AND AROUND A REPOSITORY FOR SPENT NUCLEAR FUEL

Taivo Tarandi
VBB - Stockholm, April 1983

This report concerns a study which was conducted for SKBF/KBS. The conclusions and viewpoints presented in the report are those of the author and do not necessarily coincide with those of the client.

A list of other reports published in this series during 1982, is attached at the end of this report. Information on KBS technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26) and 1981 (TR 81-17) is available through SKBF/KBS.

SUMMARY

Temperature distribution in and around the final storage has been calculated for BWR-fuel.

The results are also applicable to PWR-fuel if the amount of fuel is adjusted so that the power per canister is the same.

The calculations are made with the conservative assumption of the coefficient of thermal conductivity of 0.75 W/(m °C) in the bentonite and 3.0 W/(m °C) in the rock.

The amount of BWR fuel is about 1.4 ton per canister. The canisters are deposited 40 years after withdrawal from the reactor.

A number of different layouts in single and two-level storages have been studied.

Finally, a two-level storage has been chosen as a basis for further project work.

The maximum temperature increase of 59.2°C at the surface of the canister is reached about 30 years after the time of deposition. However, in this two-level storage there will be also a second temperature peak of 58.7°C about 600 years after the deposition. The highest temperature increase in the rock, 56.8°C, occurs about 600 years after the deposition.

At the same time as the temperature continues to sink, there is a levelling out of the local temperature differences in the storage. These differences are negligible after about 1 000 years.

After 100 000 years the temperature in the storage is only a few degrees centigrade above the initial rock temperature.

The heat from the storage reaches the ground surface about 200 years after the deposition. the maximum heat flow, 0.28 W/m^2, occurs about 2 000 years after deposition and is considered insignificant compared for example with solar energy flow of about 100 W/m^2.

CONTENTS

1. INTRODUCTION

A number of different storage layouts for the unreprocessed spent fuel have been studied since the start of the investigation of the storage problem. Temperature calculations for a design applicable 1978 are presented in (ref. 1)

As later calculations of residual power have resulted in higher values, a new calculation of the temperature distribution proved to be necessary. In what follows this initial design may be referred to as input alternativ (also Alt. 1A).

Due to the influence of different parameters such as the spacing of canisters and tunnels, thermal properties of the rock etc. a study of the variation of these parameters has been performed.

For locations where the horizontal extension available is limited layout in two planes has been studied.

Costs of the storage are influenced favourably if the thickness of the copper jacket can be decreased. The influence of this temperature is also analysed.

Temperature computations are of course closely connected with the project work on the whole. The result is that the initial design in one plane has been successively replaced by a two-plane storage - mainly due to the limited space available in some of the sites studied for the continuated project work.

As the initial temperature in the bed-rock is site-dependent the calculations are made for the initial temperature zero.

2. PREMISES

2.1 Principles of storage

The arrangement of the canisters containing the spent fuel is shown in principle in Figure 1.

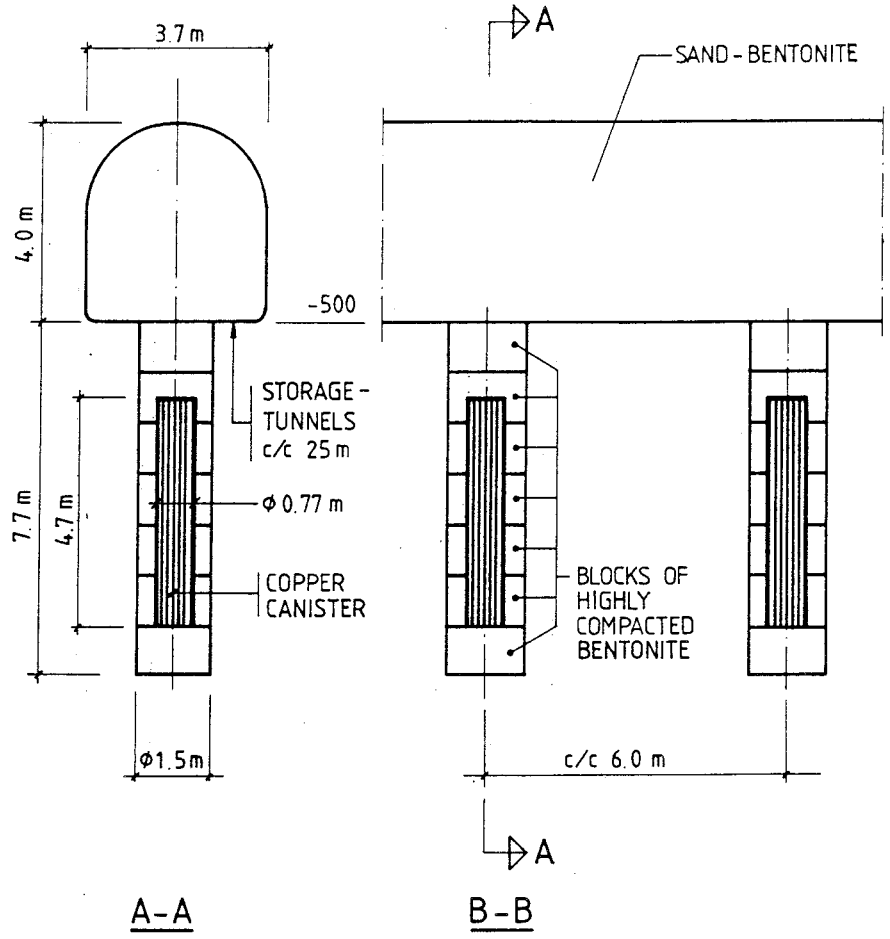


FIG. 1 FINAL STORAGE FOR SPENT FUEL.

The final repository consists of a system of parallel tunnels located about 500 m below the ground level. The spent fuel is contained in canisters of copper with wall thickness of 100 mm. The canisters are deposited in the storage 40 years after removal from the reactor.

The canisters are surrounded by a buffer material composed of highly compacted bentonite.

2.2 Different types of layouts of storage

The different configurations of storages with essential characteristics are listed in Table I, Appendix 1.

The initial power is proportional to the amount of spent fuel per canister. At 1.41 tons/canister this power is 808 W, increased to 850 W in the final design.

2.3 Loading conditions

Calculations of residual power for spent fuel are presented in (ref. 2) and shown in Appendix 2.

The power is assumed to vary in a linear logarithmic relationsship between specified points of time shown in Appendix 1.

However, for the three-dimensional (3D) calculations, in the first times of deposition the exponential power time relationship, calculated from three points of time is used.

For initial power 850 W (40 years after removal from the reactor) the following relationships have been obtained.

$$0\text{-}10\text{-}20 \text{ years } E = 509e^{-0.02525\ t} + 341$$

$$(0\text{-}20)\text{-}60 \text{ years } E = 601e^{-0.020475t} + 249$$

In the two-plane cases, the upper plane is assumed to be loaded 15 years later than the lower plane.

2.4 Material properties

In addition to the properties stated for the rock in Table I, the following values have been used for the other materials concerned.

At the beginning of deposition, 0-150 years, bentonite is assumed to be in dry condition with a thermal conductivity of 0.75 W/(m °C). Thereafter bentonite is assumed to be fully saturated with water, increasing the thermal conductivity to 1.5 W/(m °C).

The specific heat of bentonite is assumed to be 2.2 MJ/(m^3 °C).

The spent fuel is simulated with conservative material properties:

Conductivity 3 W/(m °C)
Specific heat 1.5 MJ/(m^3 °C).

3. CALCULATION METHODS

Due to economic reasons, the main part of the calculations had to be made by means of a simplified method, in what follows referred to as method 1.

During the initial period with high local gradients this method will yield results which are conservative. Therefore a three-dimensional (3D) calculation is performed for this initial period, up to 60 years for the input case. This method is called method 2.

3.1 Method 1

The calculation is executed in two stages with a finite difference code (ref. 3). At first a mean- or macro-temperature distribution is computed for the central region of storage, as shown in Figure 2. In this region the temperature distribution - at least the macro - is practically constant in the horizontal direction and a one-dimensinal model as shown in Figure 3A for one-plane and in Figure 3B for two-plane case is applied.

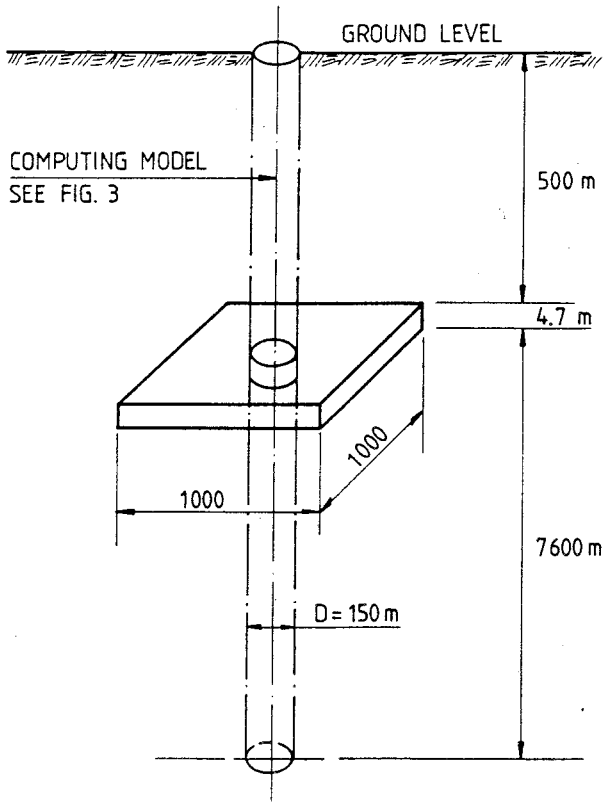


FIG. 2 SITUATION PLAN

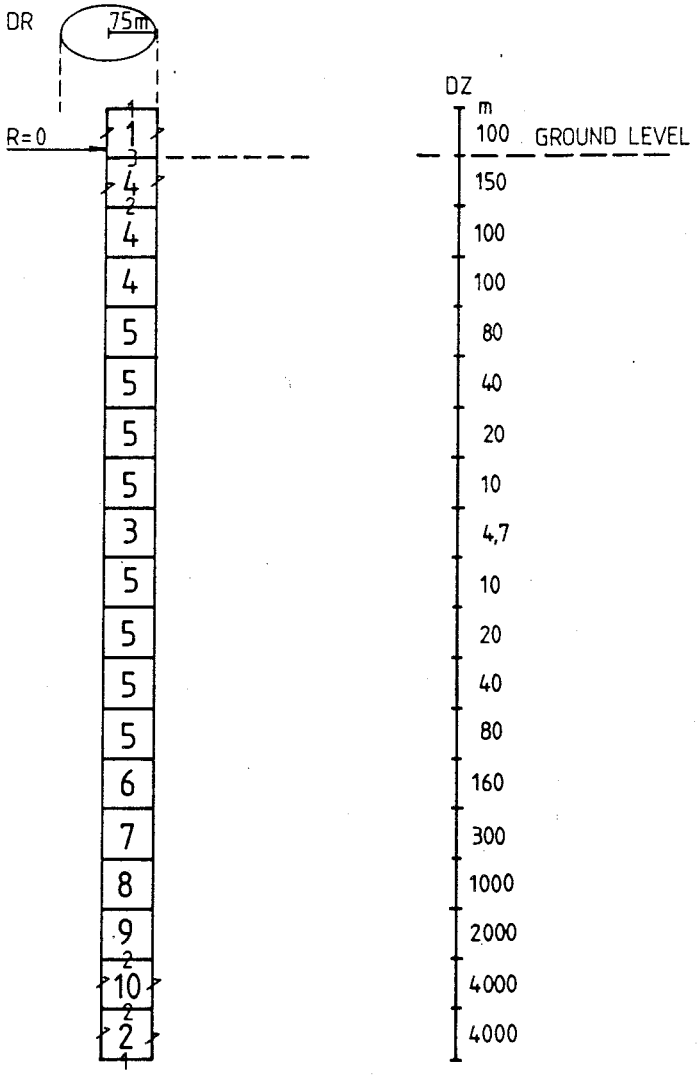


FIG. 3A ONE-DIMENSIONAL COMPUTING MODEL FOR MACROTEMPERATURE.

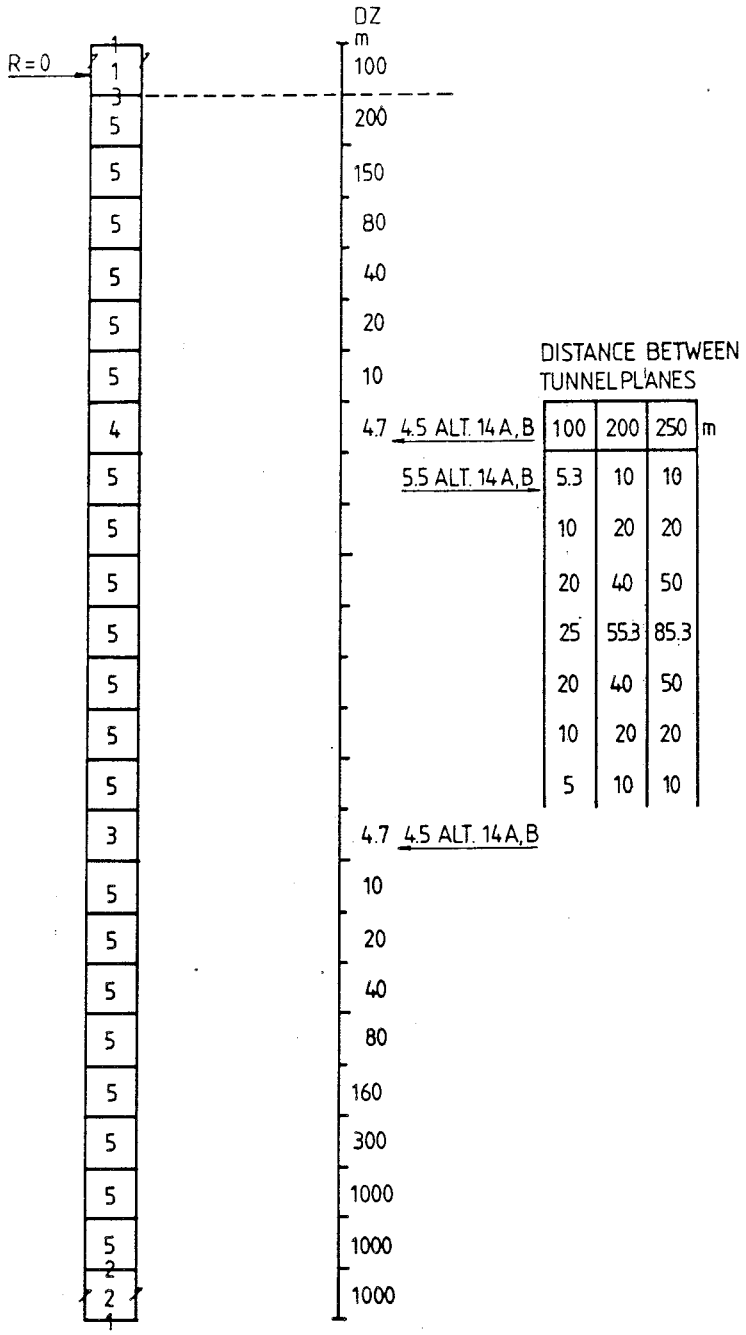


FIG. 3B MACRO MODEL FOR 2-PLANE DESIGN.

To verify the assumption of constant temperature distribution in the central region, a two-dimensional model according to Figure 4 has been used at an earlier stage of the calculations.

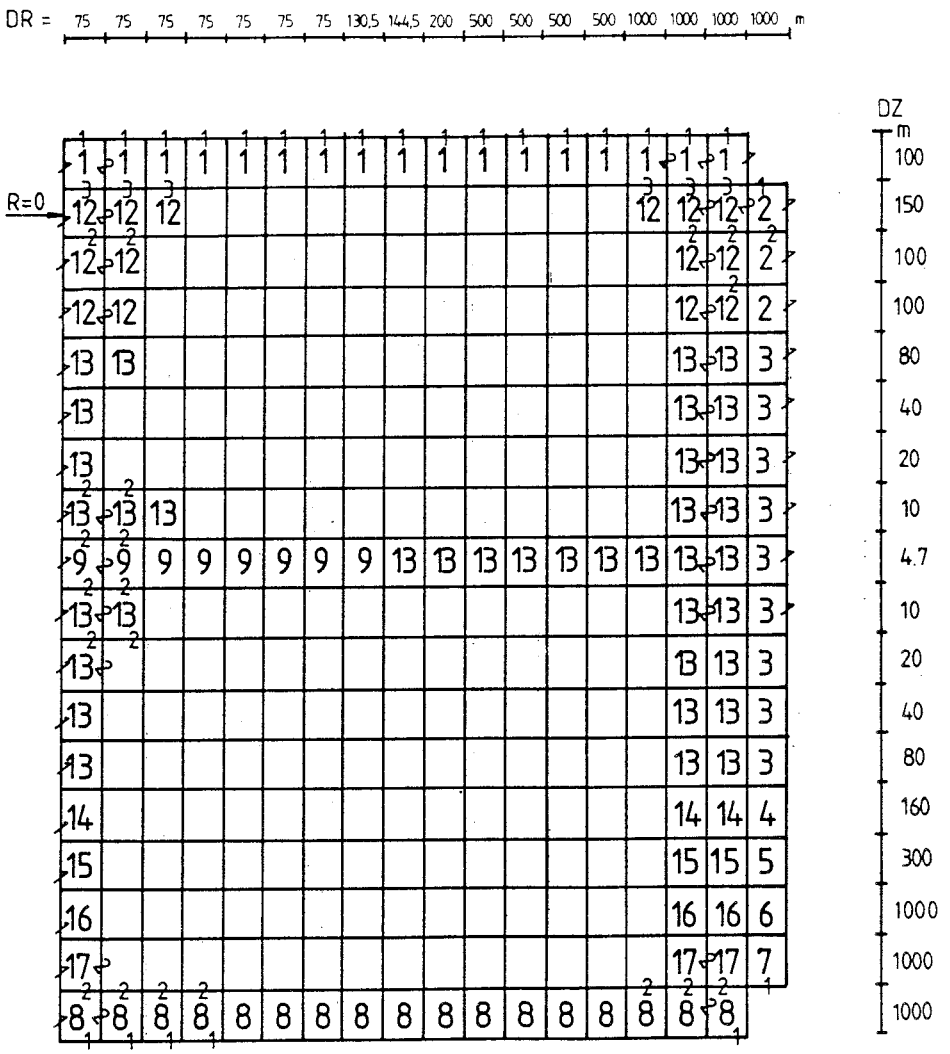


FIG. 4 TWO DIMENSIONAL COMPUTING MODEL FOR MACROTEMPERATURE.

With the output from these rough models as input a new calculation is made with a finer mesh, micromodel 1, according to Figure 5, corresponding to half a tunnel spacing as a ring model with large radius.

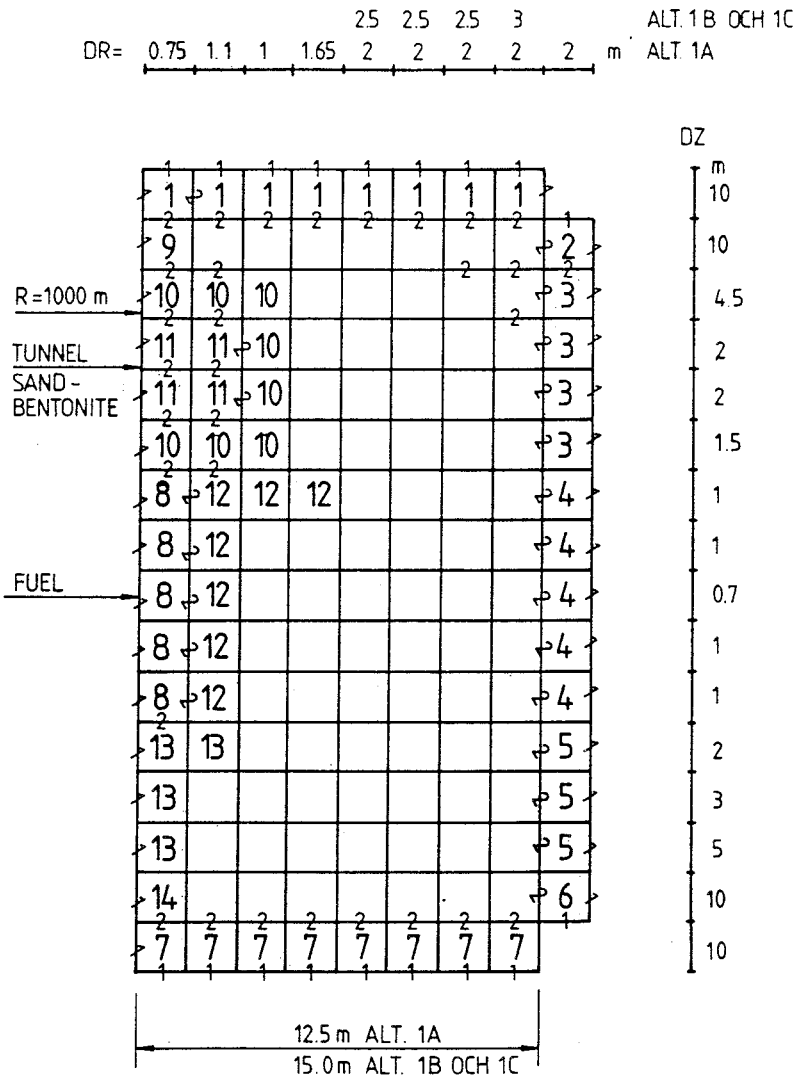


FIG. 5 COMPUTING MODEL FOR MICROTEMPERATURE 1.

Finally - as a third stage - the local temperature distribution nearest the canister is calculated analytically as stationary temperature for long cylinders according to Figure 6, using the formula

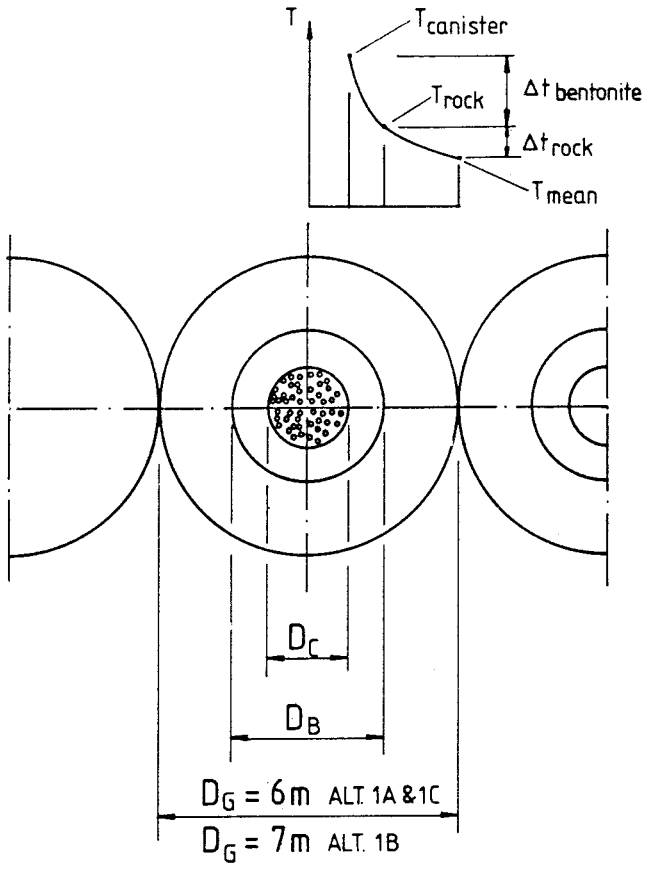


FIG. 6 COMPUTING MODEL FOR MICROTEMPERATURE 2.

$$T = \frac{Q \cdot \ln(d_y/d_i)}{l \cdot 2\pi \cdot \lambda} \qquad (3.1)$$

där

Q = power at the time, W
l = length of the canister, m
d_y = outer diameter of the cylinder
d_i = inner diameter of the cylinder
λ = thermal conductivity, W/(m °C)

As regards the boundary conditions, the macromodel is assumed to be insulated at the outer surfaces, except at the ground level where zero temperture is held constant with a convective heat transfer coefficient of 10 W/(m²· °C) between atmosphere and rock.

In micromodel 1 the temperatures from macromodel are input as constant boundary temperatures.

3.2 Method 2

This is a three-dimensional analysis using a model as shown in Figure 7. Due to code limitations only elements in the shape of parallelepipeds can be used.

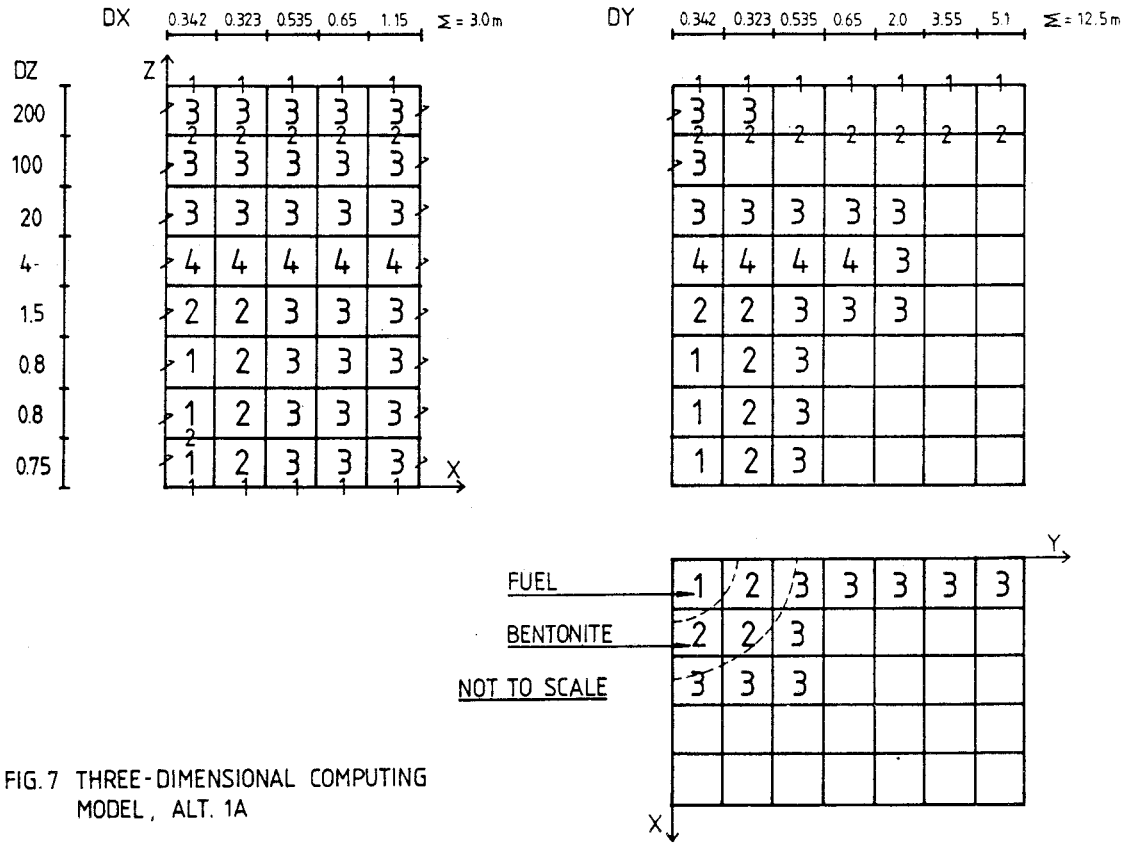


FIG. 7 THREE-DIMENSIONAL COMPUTING MODEL, ALT. 1A

3.3 A single canister

For comparison, an analysis for a single canister infinetely apart from other canisters, has been performed with an axisymmetrical model.

4. RESULTS

4.1 Method 1

Temperature distribution at the centre of storage is shown in Figure 8A for one-plane design and in Figures 8B and 8C for two-plane design with 100 m and 250 m resp. between the planes. Figure 8B indicates that in the case 14B the maximum macro-temperature is about 7°C lower than in the case 14A due to higher thermal conductivity.

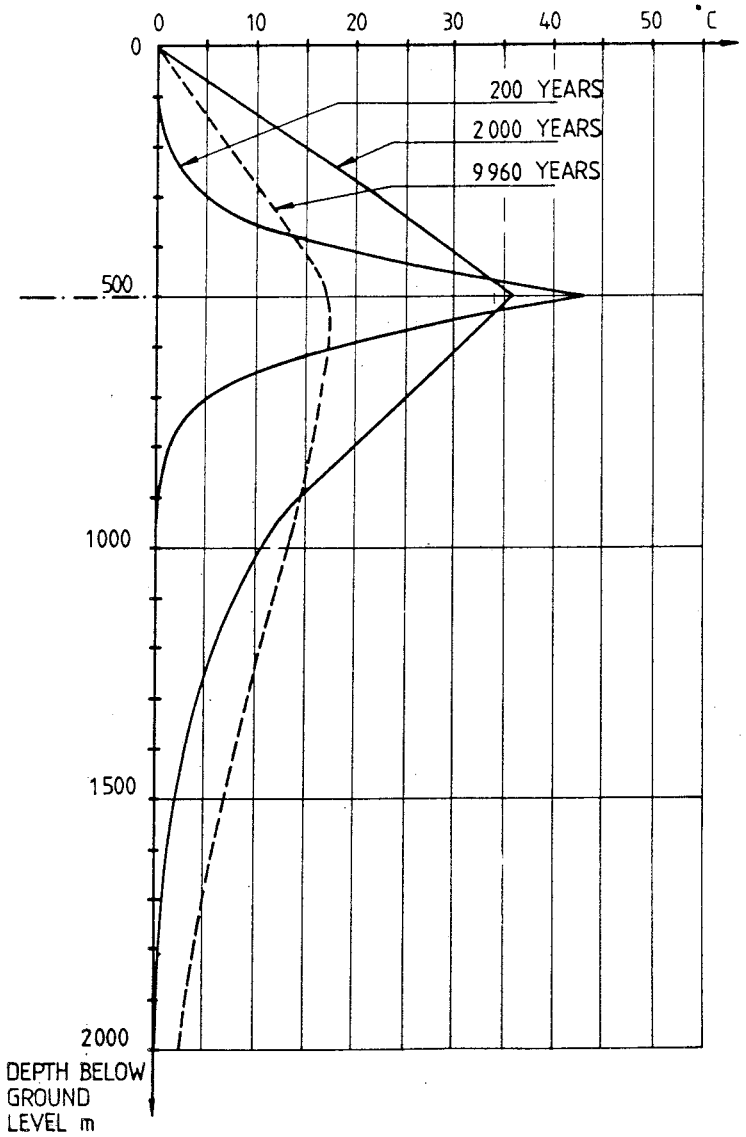


FIG. 8 A MACROTEMPERATURE DISTRIBUTION AT CENTRUM ALT. 1A

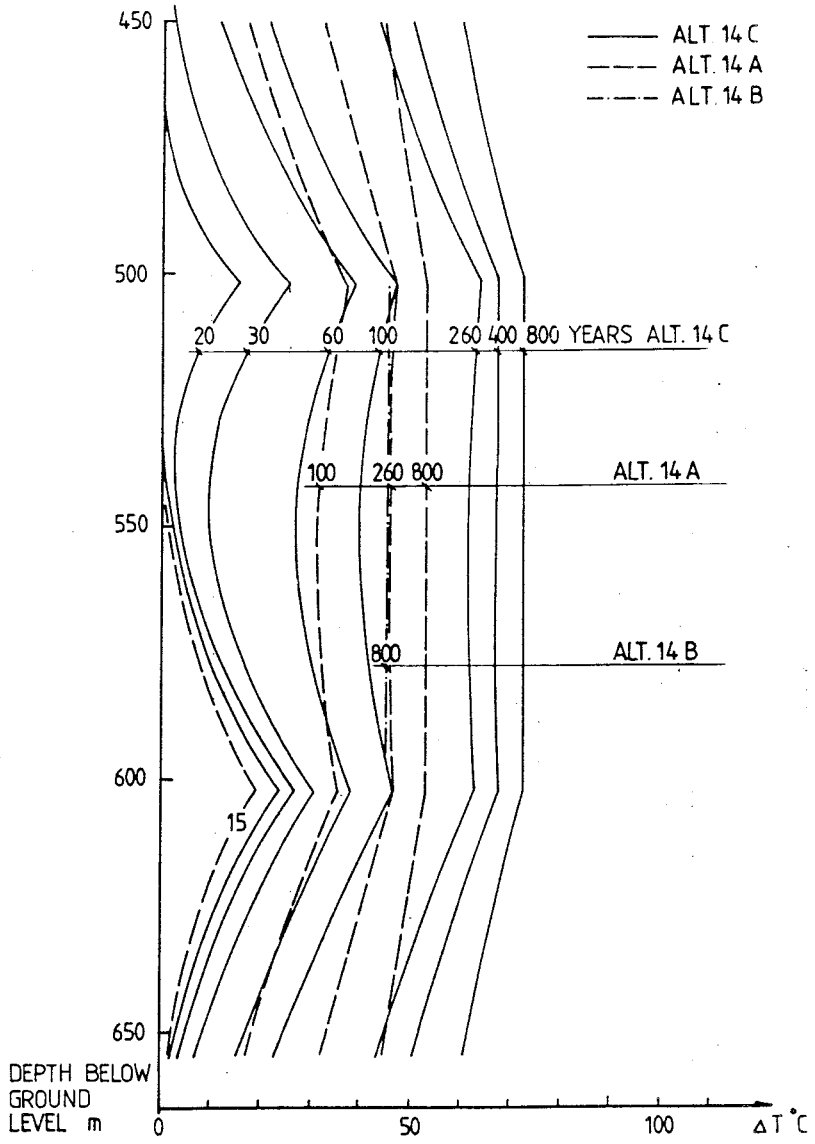


FIG. 8 B TEMPERATURE DISTRIBUTION AT CENTRUM
2-PLANE DIST. 100 m

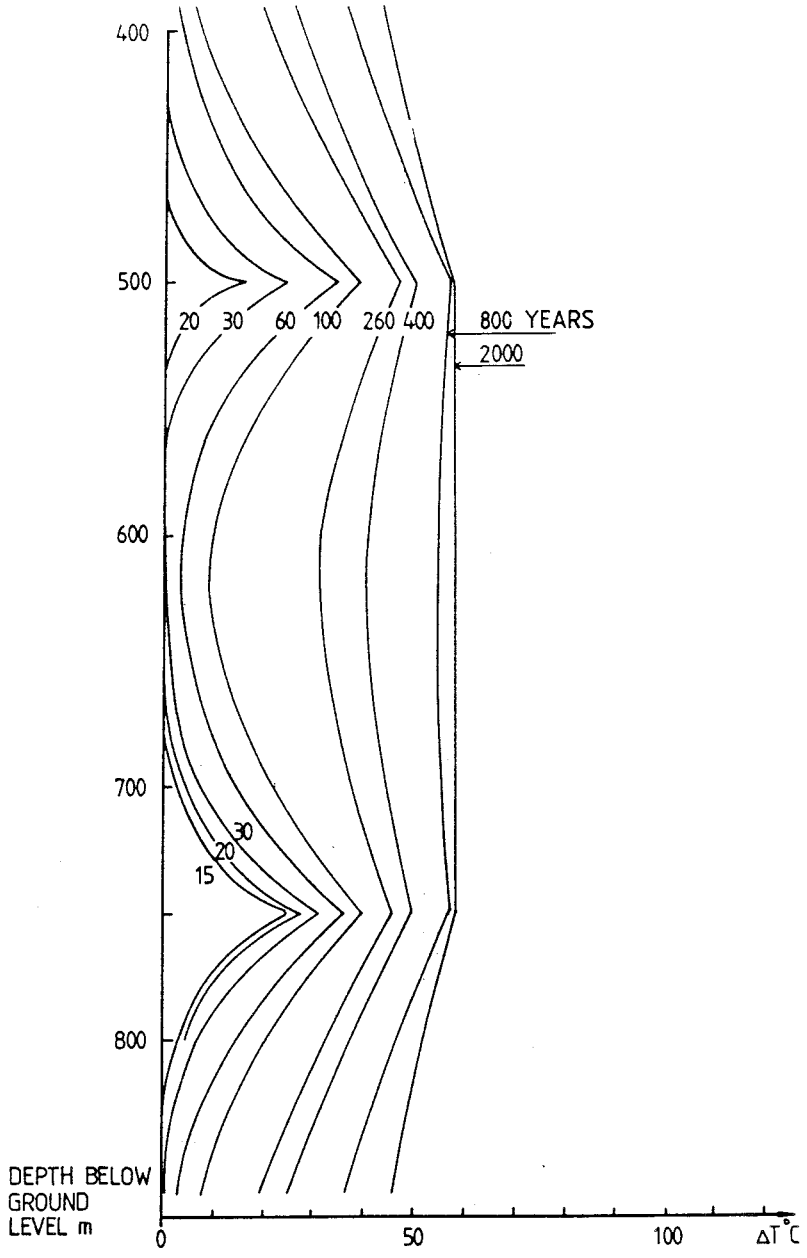


FIG. 8C TEMPERATURE DISTRIBUTION AT CENTRUM
2-PLANE DIST 250 m

Figures 9A-10B shows isotherms for the input and output cases 200 and 960 years resp. after deposition.

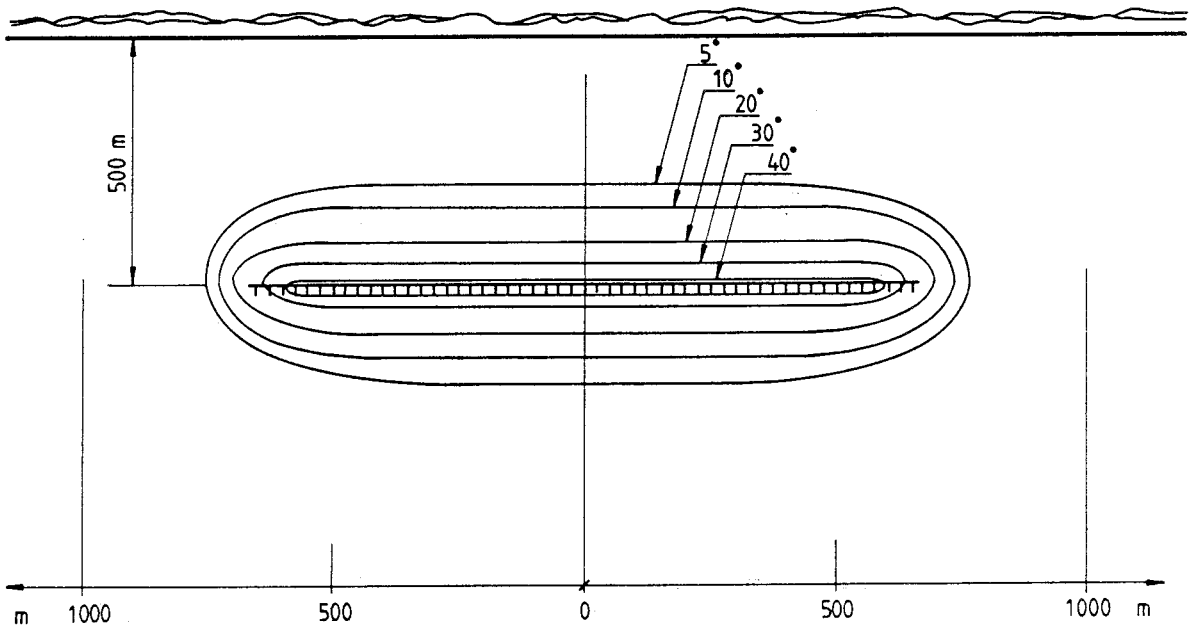


FIG. 9A TEMPERATURE INCREASE IN BED-ROCK AROUND THE FINAL STORAGE
200 YEARS AFTER DEPOSITION ALT. 1A

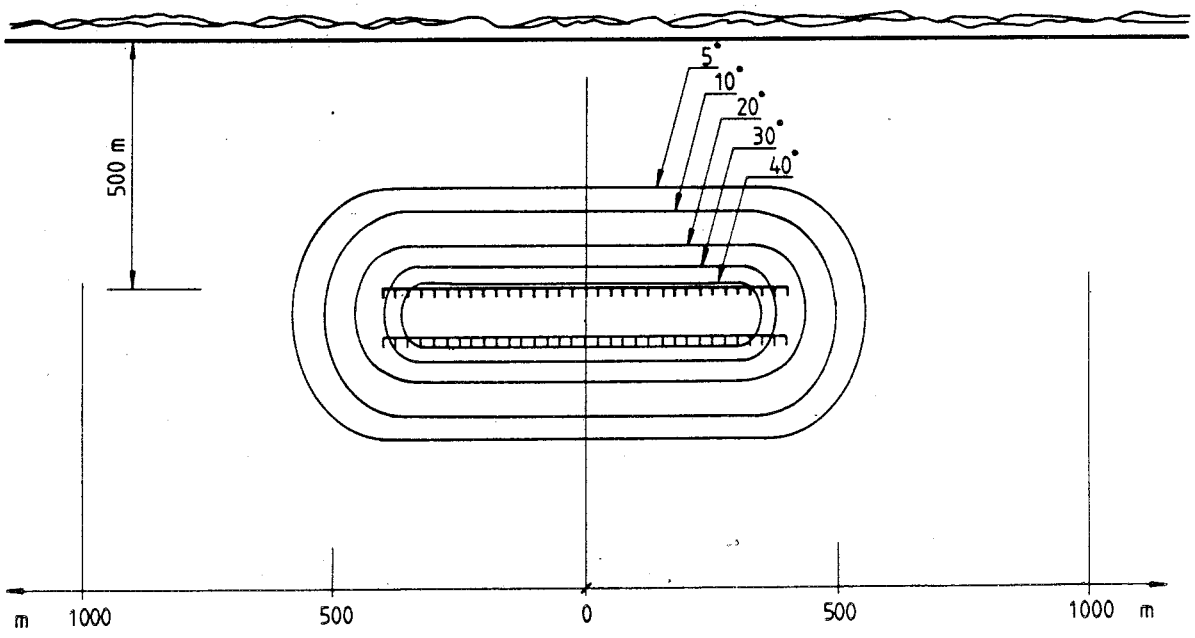


FIG. 9B TEMPERATURE INCREASE IN BED-ROCK AROUND THE FINAL STORAGE
200 YEARS AFTER DEPOSITION. ALT. 14A

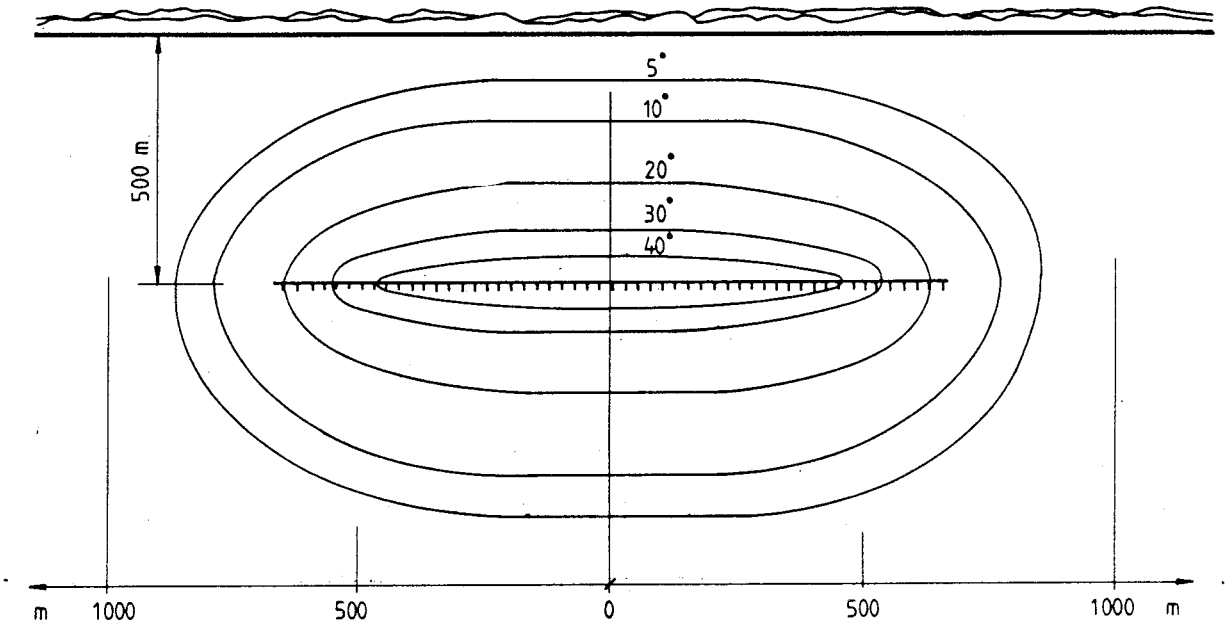


FIG. 10A TEMPERATURE INCREASE IN BED-ROCK AROUND THE FINAL STORAGE
960 YEARS AFTER DEPOSITION ALT. 1A

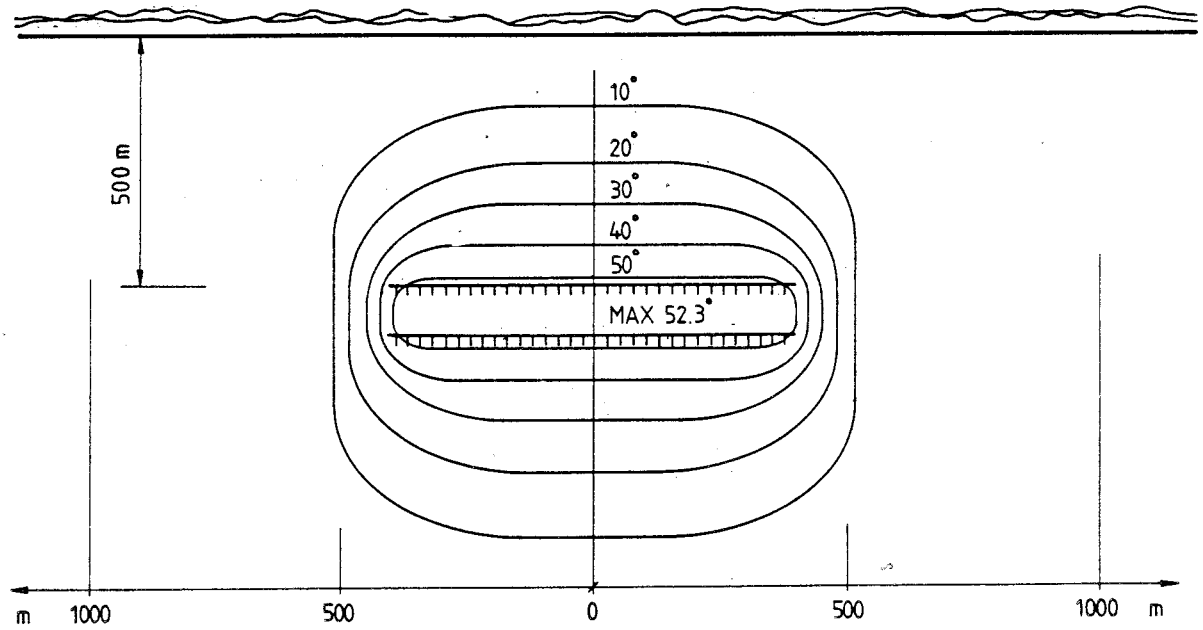


FIG. 10B TEMPERATURE INCREASE IN BED-ROCK AROUND THE FINAL STORAGE
960 YEARS AFTER DEPOSITION ALT. 14 A

Temperature variation as function of time is shown in Figures 11A-11F. For the Alt. 1A (input case) the maximum temperature on the canister surface 64°C is reached in about 20 years after deposition. For Alt. 14A (output case) Figure 11F the corresponding temperature in the upper plane is 65.3°C. Here, 1.3°C is due to influence from the lower plane about 35 years after deposition. In this case, however, a second peak of temperature, 58.7°C, occurs about 600 years after deposition.

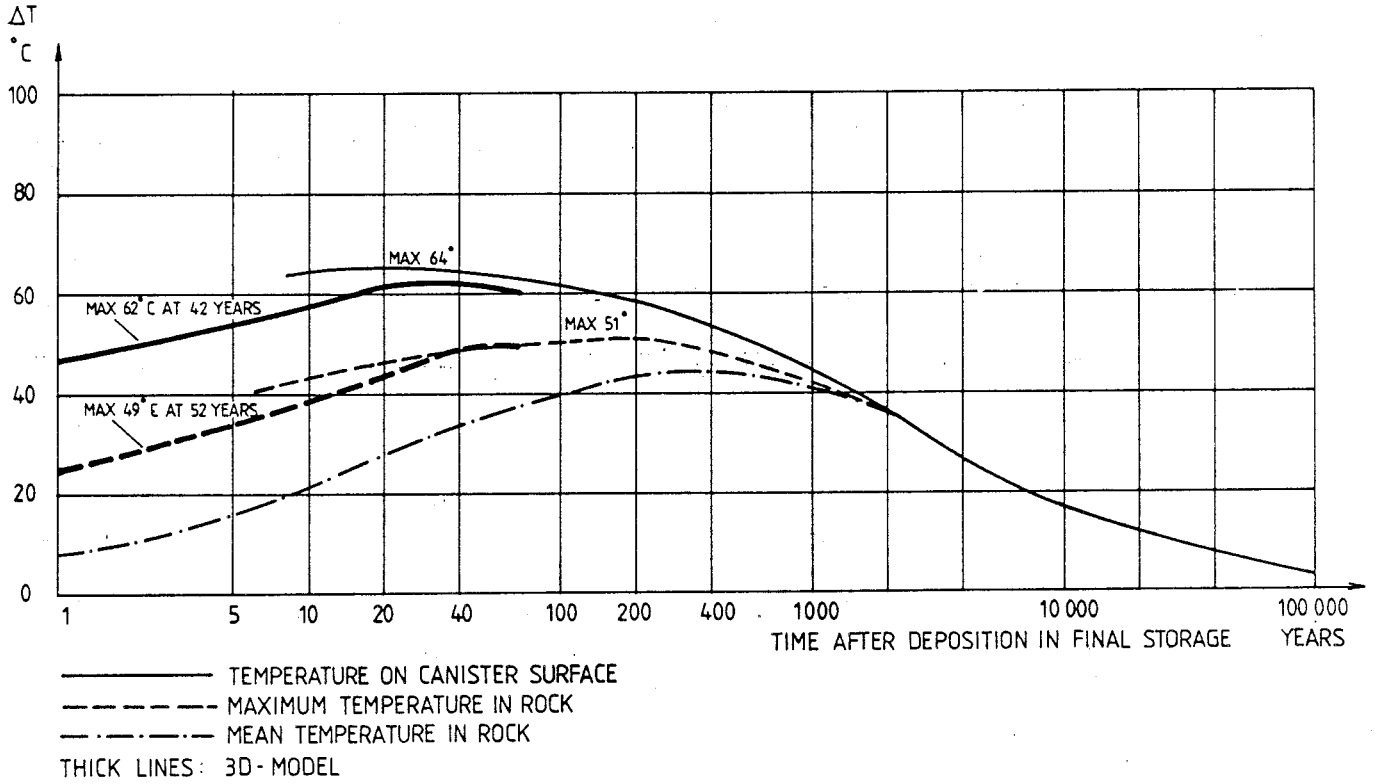


FIG. 11A VARIATION OF TEMPERATURE AT CENTRUM ALTERNATIVE 1A.

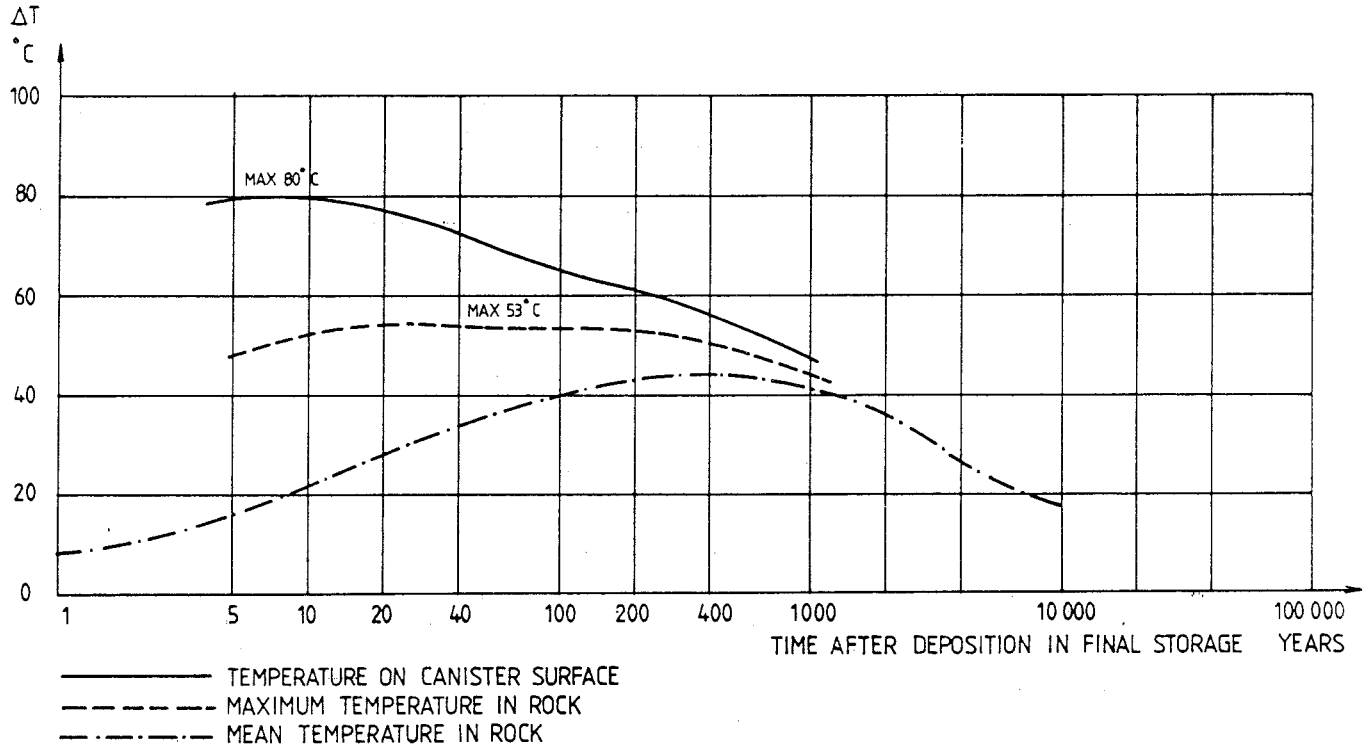


FIG. 11 B VARIATION OF TEMPERATURE AT CENTRUM
ALT. 1 B G = 1.93 TON

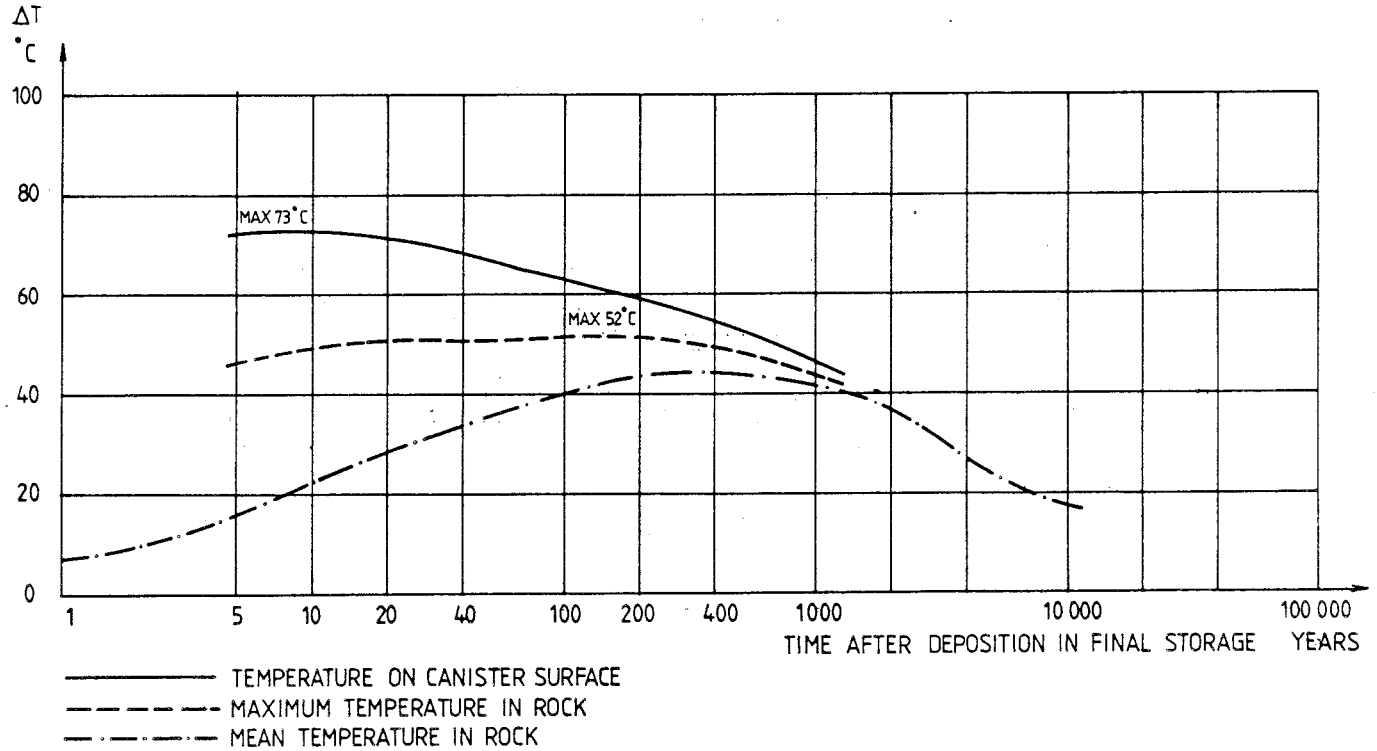


FIG. 11 C VARIATION OF TEMPERATURE AT CENTRUM
ALT. 1C G = 1.66 TON

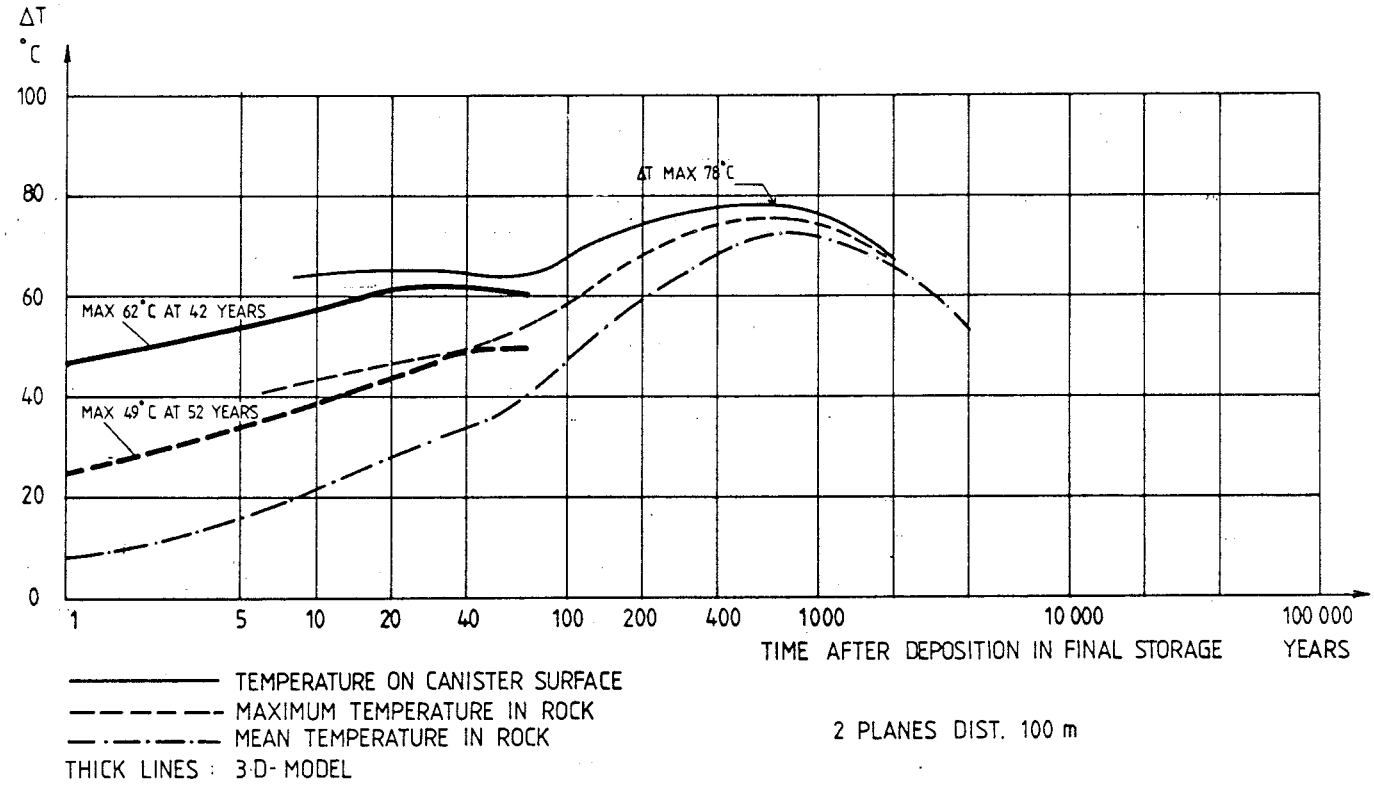


FIG. 11 D VARIATION OF TEMPERATURE AT CENTRUM
ALTERNATIVE 14 A

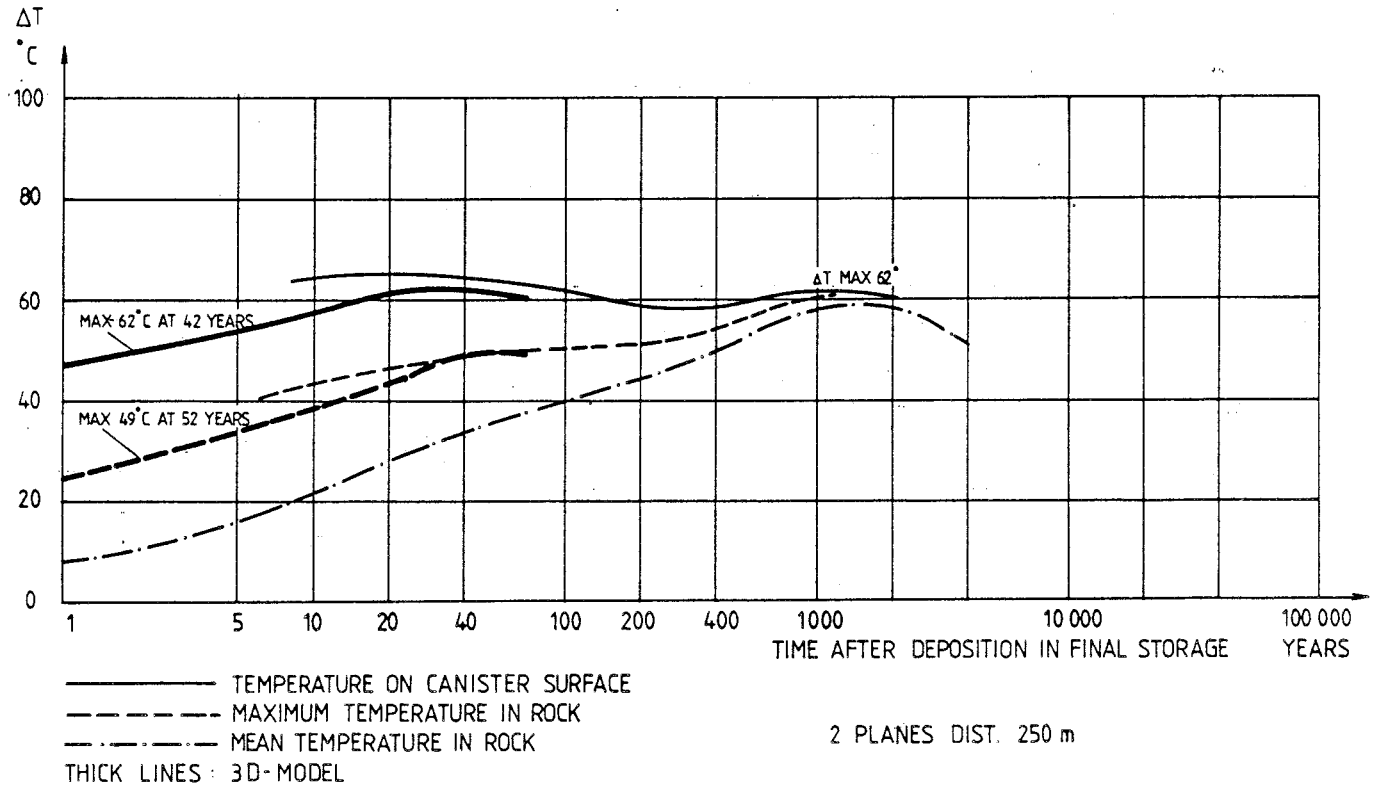
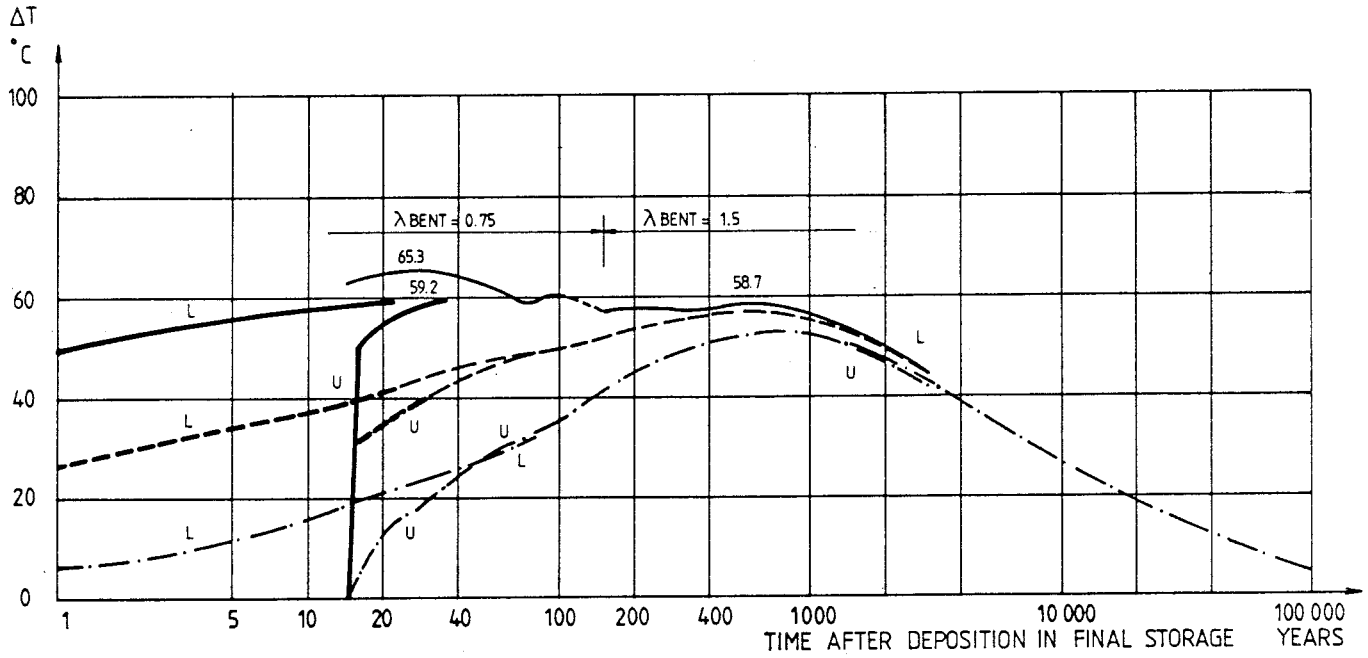


FIG. 11 E VARIATION OF TEMPERATURE AT CENTRUM
ALTERNATIVE 15



TEMPERATURE ON CANISTER SURFACE
MAXIMUM TEMPERATURE IN ROCK
MEAN TEMPERATURE IN ROCK
THICK LINES 3D-CALCULATION
L = LOWER PLANE
U = UPPER PLANE

E_0 = 850 W/CANISTER 40 YEARS AFTER REMOVAL FROM REACTOR
DIAMETER OF CANISTER 0.8 m
LENGHT OF CANISTER 4.5 m
SPACING OF CANISTER 6.0 m
SPACING OF TUNNELS 33.33 m
DISTANCE BETWEEN TUNNELPLANES 100 m

FIG. 11 F VARIATION OF TEMPERATURE AT CENTRUM.

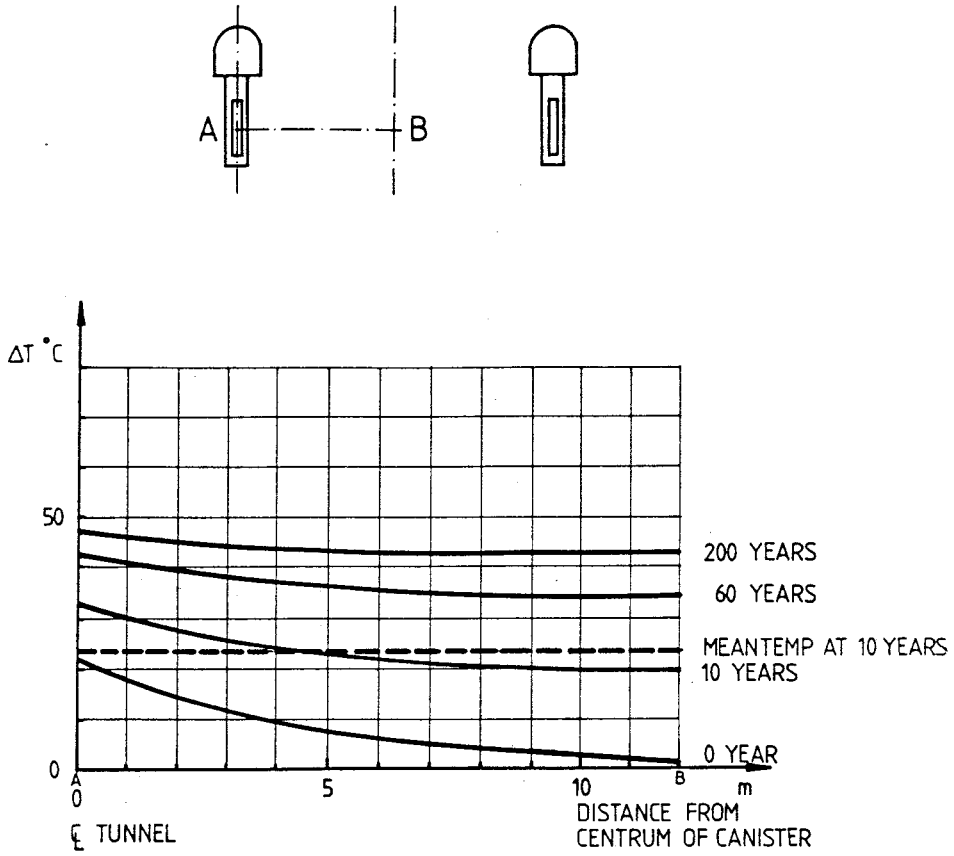


FIG. 12A TEMPERATURE DISTRIBUTION
IN PLANE A-B. ALT. 1A

Temperature distribution between tunnels is shown in Figure 12A.

4.2 Method 2

Variation of temperature as function of time is shown in Figure 11A for the input case and in Figure 11F for the output case.

In the one-plane case the maximum temperature is 62°C after about 42 years after deposition. This value is thus only 2°C lower than the value obtained by the approximate method 1.

In the two-plane case, Figure 11F, the first maximum value is 59.2°. In this case method 1 yields about 6°C higher temperature.

Temperature distribution adjacent to the canister is shown in Figure 12 B. It may be observed that it is almost axisymmetrical to a distance corresponding to half the spacing of the canisters. The difference between the maximum and minimum values is only about 2°C (of 40°C).

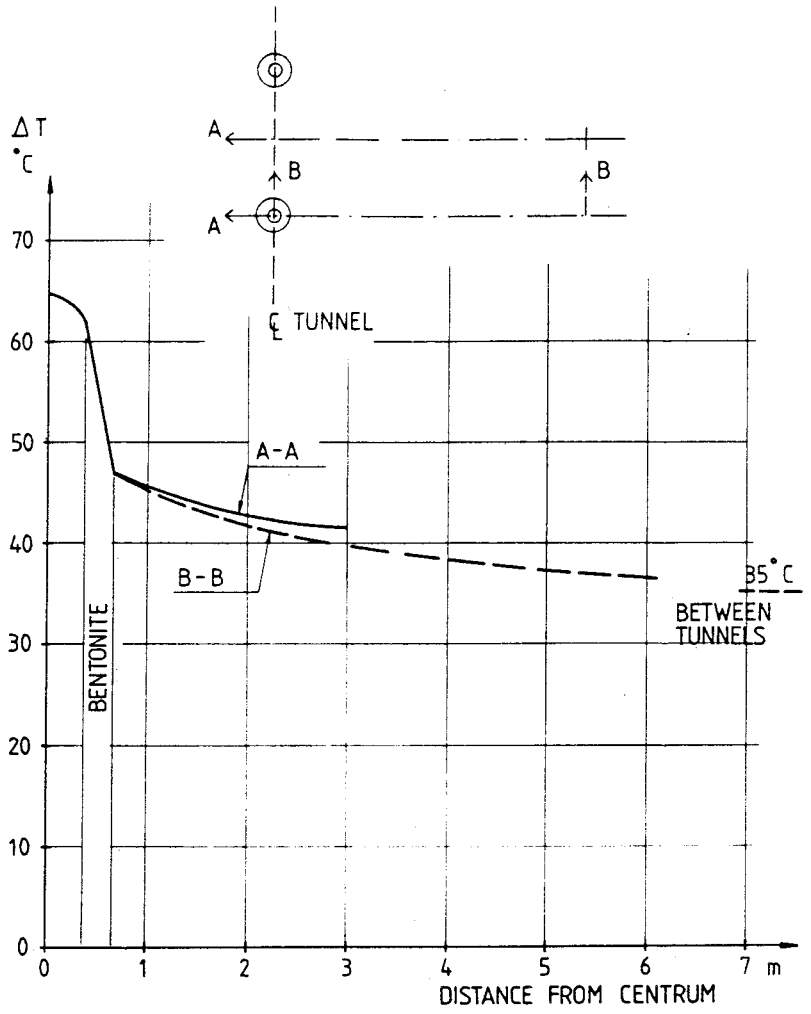


FIG. 12 B TEMPERATURE DISTRIBUTION AROUND THE CANISTER 42 YEARS AFTER DEPOSITION.

The results of the different cases are summarized in Figures 13 and 14. These figures can be used to estimate temperatures for configurations other than those computed here, such as for the output case, for which 3D-calculations have not been made.

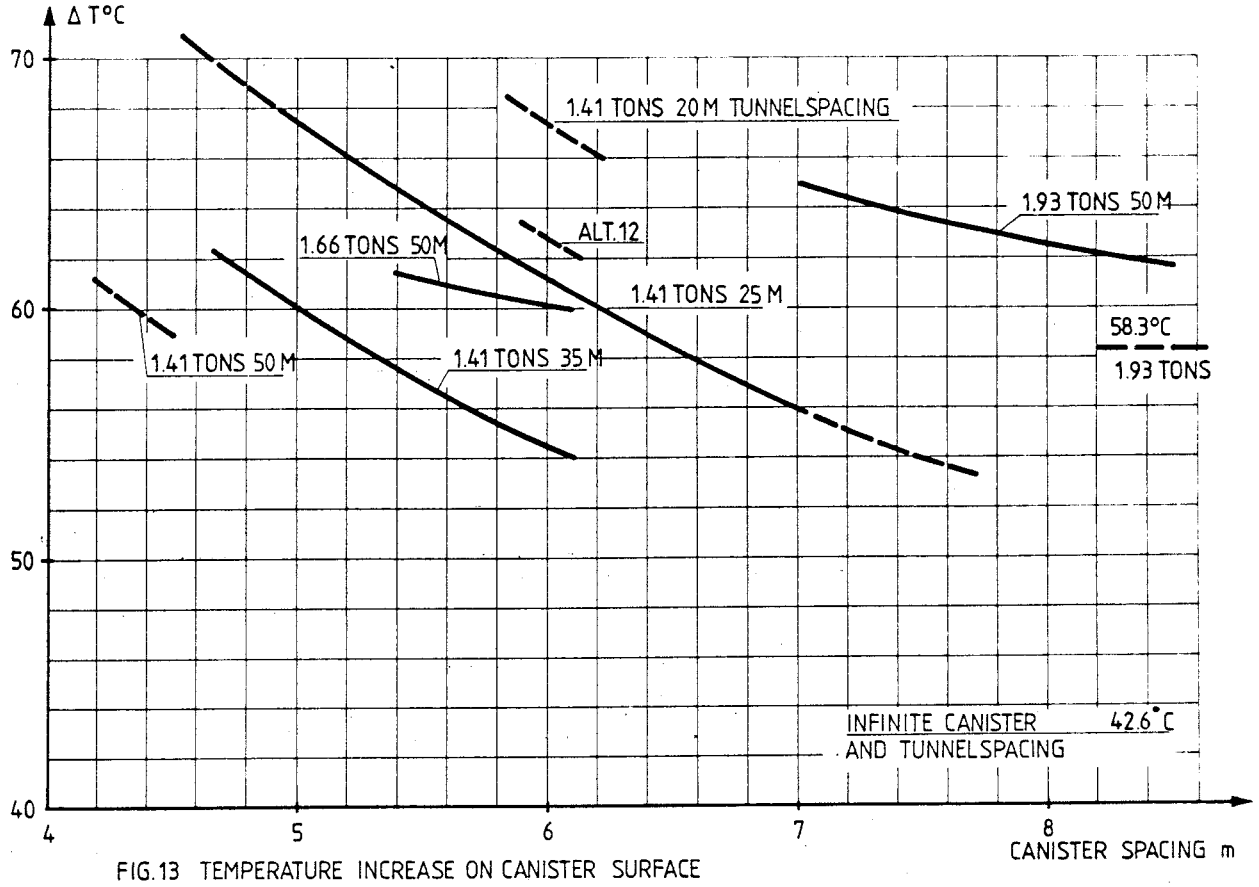


FIG.13 TEMPERATURE INCREASE ON CANISTER SURFACE

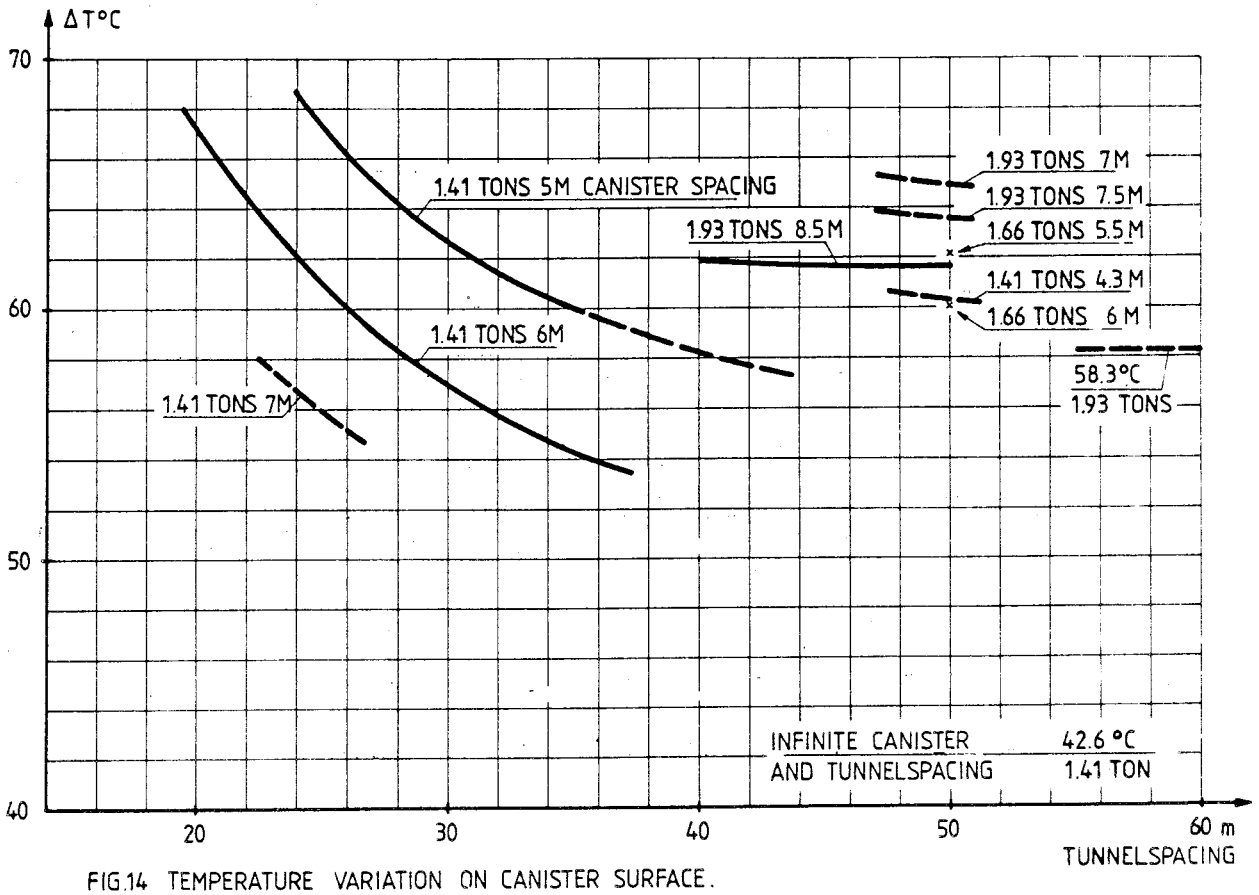


FIG.14 TEMPERATURE VARIATION ON CANISTER SURFACE.

From Figure 14 the temperature 55°C is obtained for tunnel spacing 33.33 m, canister spacing 6 m and initial power 808 W (1.41 tons). For the output case with 850 W this corresponds to

$$\frac{850}{808} \times 55 = 57.9°C$$

To this should be added 1.3°C which is the influence from the lower plane after 35 years.

The maximum temperature at the first peak is thus 59.2°C.

In addition there is a slight difference in the dimensions of the canister. Thus the outer diameter of the canister is now 0.80 instead of 0.77 for the initial case. This means a decrease in the local temperature of about 6 % near the canister. At the same time, the length of the canister is decreased from 4.7 m to 4.5 m, which corresponds to an increase of about 4 %. These effects may be assumed approximately to cancel out each other.

4.3 A single canister

Temperature distribution for a single canister of type 1A (input case) is shown in Figures 15-16.

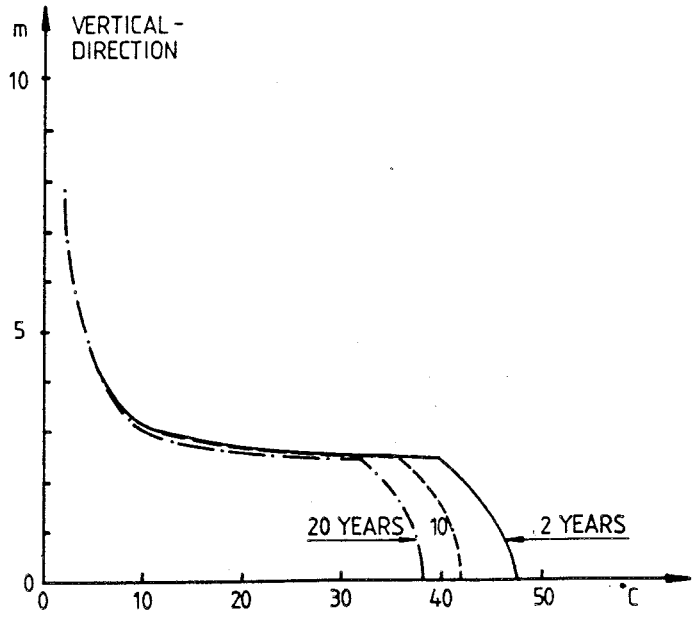


FIG. 15 TEMPERATURE DISTRIBUTION ALONG THE AXIS OF CANISTER.

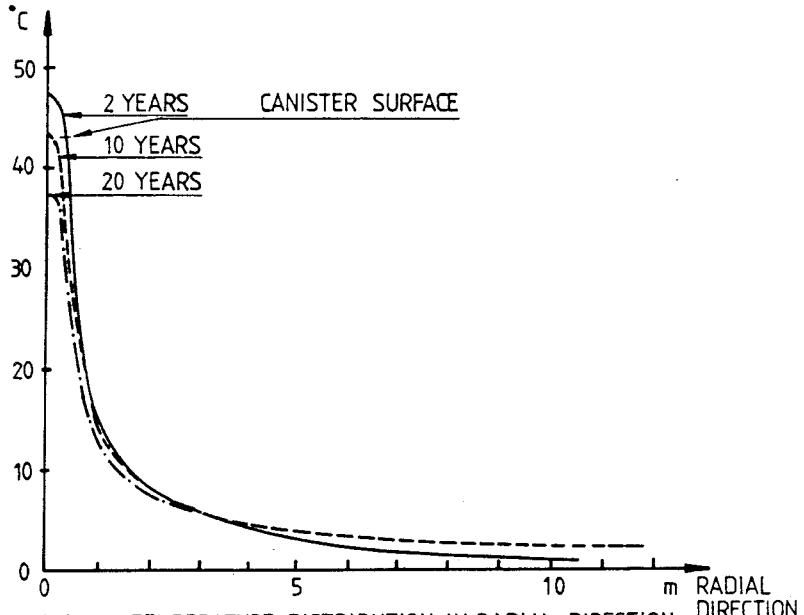


FIG. 16 TEMPERATURE DISTRIBUTION IN RADIAL DIRECTION

The maximum temperature, 42.6°C occures about two years after deposition. For an infinetely long canister the corresponding temperature is 52.6°C.

Thus for improved accuracy in method 1 a correction factor of

$$\frac{42.6}{52.6} = 0.81$$

could be introduced in the formula (3.1).

4.4 Heat flow at ground level

Heat flow at ground surface is shown in Figure 17 for the two reference cases. The heat flow reaches the ground level about 200 years after the deposition. The maximum value occours after about 2000 years and is 0.21 and 0.28 W/m^2 resp.

These are very low values as compared with for example solar energy heat fow of about 100 W/m^2 (ref. 4).

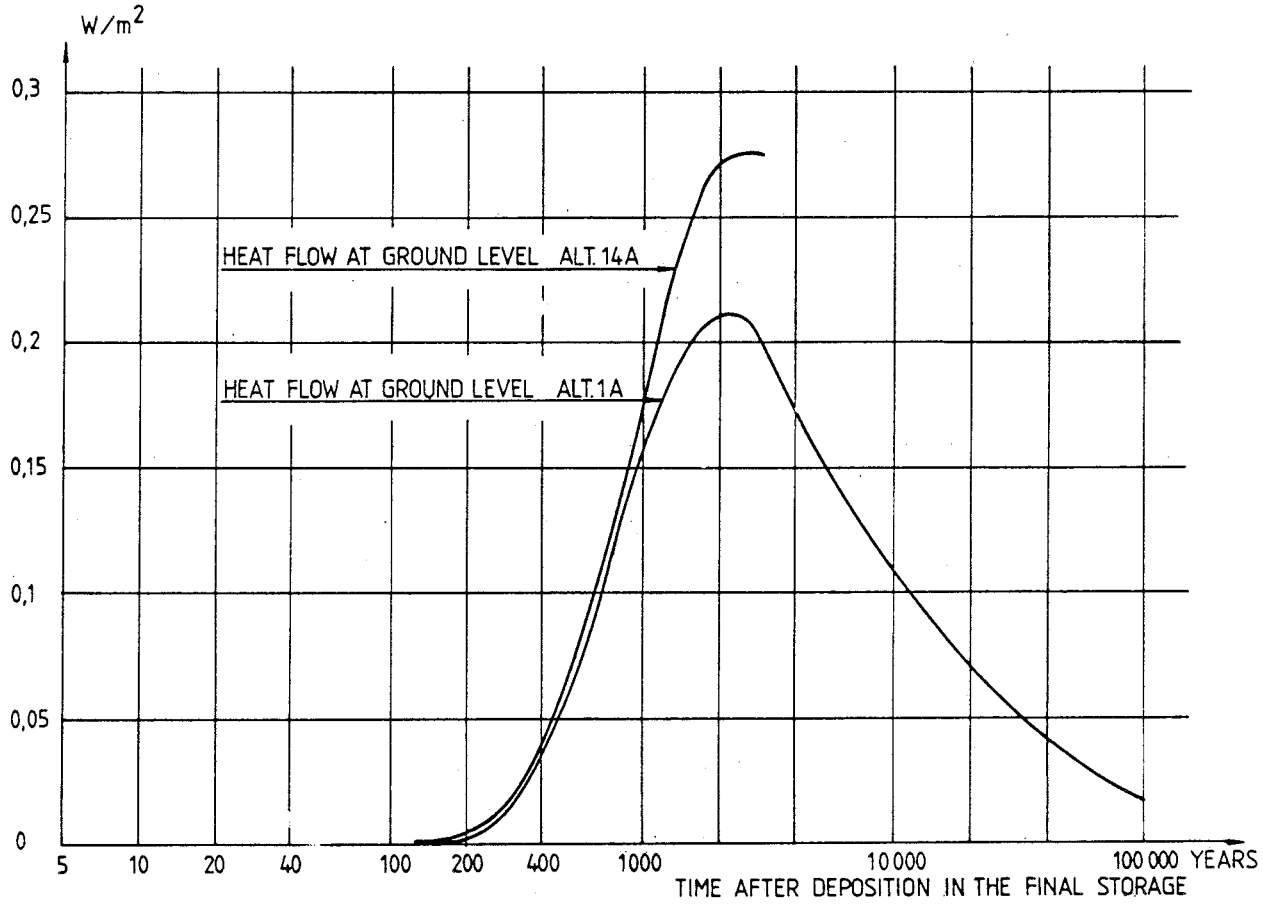


FIG. 17 HEAT FLOW AT GROUND LEVEL.

4.5 Influence of gaps

No account has been taken of gaps between bentonite, canister and rock. These gaps will be filled with powder of bentonite, which can have a lower thermal conductivity than the bentonite itself. Conservatevely it is assumed that the thermal conductivity in the gap is 0.3 W/(m·°C).

The increase of temperature in the gap is calculated from

$$\Delta T_g = \frac{Q \; s}{l \cdot \pi \cdot d} \left(\frac{1}{\lambda_{gap}} - \frac{1}{\lambda_{bent}} \right)$$

where

Q = power in W
s = thickness of the gap in m
l = length of the canister = 4.5 m
d = diameter of the canister in m
λ_{gap} = thermal conducivity in the gap = 0.3 W/(m °C)
λ_{bent} = thermal conductivity of the bentonite = 0.75 W/(m °C)

At time 15 years after deposition with Q = 690 W is obtained

at the canister

with
s = 0.030 m and
d = 0.800 m

ΔT_g = 4.1°C

at the rock

with
s = 0.050 m and
d = 1.500 m

ΔT_g = 3.3°C

Thus the total influence from the gaps is about 7.5°C.

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1. Tarandi, T., Temperature calculations for final storage for spent fuel, KBS Tecnical Report 46, June 1978 (in Swedish).

2. Eklund O., Calculation of the burn-up dependent parameters of the core fuel in a PWR- and BWR-reactor by the computer code ORIGEN 2, KBS AR.82-09, Table 9.

3. Tarandi T., Computer programs and their application for temperature and stress analysis of reactor pressure vessels. 1st Int. Conference in Pressure Vessel Technology, Delft, September 29-October 02 (1969).

4. Kauer E., The potential of solar energy, Atomkernenergie (ATKE) Bd. 25 (1975) Lfg. 3, p.162.

TABLE I CHARACTERISTICS OF STORAGES

1. One-plane design

2- and 3-dimensional calculations

Alt.	Distance between tunnel-planes m	Diameter of canister m	Spacing of canister m	Spacing of tunnels m	Thermal conductivty of rock W/(m °C)	Specific heat of rock MJ/(m³ °C)	Weight of spent fuel tons/ canister
2- och 3-dimensional calculations							
1A		0.77	6	25	3.0	2.0	1.41
1B1		0.826	7	50	3.0	2.0	1.93
1B2		0.826	7.5	50	3.0	2.0	1.93
1B3		0.826	8.5	50	3.0	2.0	1.93
1B4		0.826	8.5	40	3.0	2.0	1.93
1B5		0.826	8.5	60	3.0	2.0	1.93
2		0.77	6	25	3.6	1.8	1.41
3		0.77	6	25	2.0	2.5	1.41
4		0.77	5	25	3.0	2.0	1.41
5		0.77	7	25	3.0	2.0	1.41
6		0.77	6	20	3.0	2.0	1.41
7		0.77	6	35	3.0	2.0	1.41
8		0.77	8	25	2.0	2.5	1.41
9 (A)		0.77	5	35	3.0	2.0	1.41
10(A)		0.77	4.3	50	3.0	2.0	1.41
11(C)		0.798	6	50	3.0	2.0	1.66
12		0.57 [1]	6	35	3.0	2.0	1.41
13		0.798	5.5	50	3.0	2.0	1.66

1) Copper thickness 100 mm

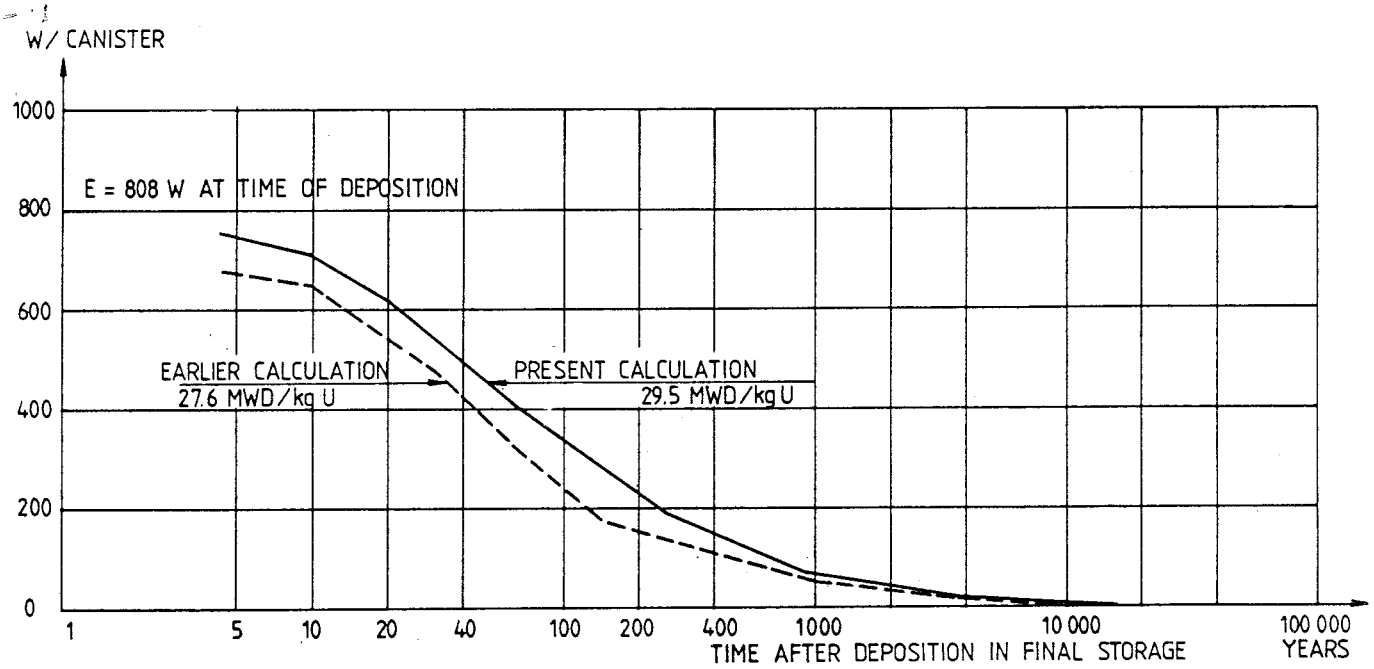
2-dimensional calculations only

1B0	0.826	7	30	3.0	2.0	1.93
1C	0.798	6	30	3.0	2.0	1.66

2. Two-plane design

2-dimensional calculations only

Alt.	Distance between tunnel-planes m	Diameter of canister m	Spacing of canister m	Spacing of tunnels m	Thermal conductivty of rock W/(m °C)	Specific heat of rock MJ/(m³ °C)	Initial power W/ canister
14A	100	0.80	6	33.33	3.0	2.0	850
14B	100	0.80	6	33.33	3.6	2.25	850
14C	100	0.77	6	25	3.0	2.0	808
15	250	0.77	6	25	3.0	2.0	808



RESIDUAL POWER FOR 1.41 TONS

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